An Examination of Along-Track Interferometry for Detecting Ground Moving Targets

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***Abstract*— Along-track interferometry (ATI) is an interferometric synthetic aperture radar technique primarily used to measure Earth-surface velocities. While developed for oceanographic applications, ATI techniques also hold promise for detecting moving ground targets. We present results from an airborne experiment demonstrating phenomenology specific to the context of observing discrete ground targets moving amidst a stationary clutter background. The results indicate that ATI techniques are able to detect ground targets that may be too slow or too dim for other detection methods. The results also show that ATI techniques are still limited by low target reflectivity and nonuniform motion, however.**

I. Introduction

Synthetic aperture radar (SAR) along-track interferometry (ATI) is a technique that can be used to map Earth-surface velocities. The ATI technique involves the acquisition of SAR data from phase centers that are separated in the direction of the platform flight path. SAR images formed from these two phase centers are therefore characterized by a temporal baseline equal to the time required for the platform to travel the distance of the along-track offset of the phase centers. Ideally, stationary elements of the imaged scene contribute identically to the two images while moving targets in the scene exhibit phase shifts between the two images. The phase of an interferogram formed from the two images consequently depicts surface movements in the imaged scene.

ATI techniques have been developed mainly in the context of mapping ocean surface currents for science applications, wherein velocity accuracies on the order of a few centimeters per second have been reported from airborne platforms [1]. ATI techniques are less well developed for the application of detecting discrete ground targets amidst a stationary background, however [2]–[4]. This paper reports on an airborne experiment undertaken in order to validate ATI performance models specific to ground moving target indication (GMTI).

II. Background

ATI performance in the GMTI context differs from the oceanographic context largely as a result of the stationary clutter background that is present in the former case. That is, in the GMTI context, the reflected radar energy from the stationary ground surface competes with and often overwhelms the radar echoes from a moving target of interest. Reference [4] provides an overview of GMTI-specific ATI performance models. In the remainder of this section, we briefly review some ATI effects specific to GMTI.

We adopt a Cartesian coordinate system in which the x, y, and z directions correspond to the along-track, across-track, and vertical directions for a platform flying level over a flat ground surface. Let ρ_0 be the slant range from the platform to the target at the center of the synthetic aperture. We assume that the baseline (physical separation) between the two SAR phase centers contains only an along-track component B_x.

If the focusing parameters (Doppler centroid and rate) used for SAR azimuth compression are selected with reference to the stationary background as is typical for most SAR applications, a moving target may be significantly misfocused in the SAR imagery [4]. The along-track component of the target velocity v_x primarily causes an error in the Doppler rate (quadratic coefficient) of the target phase history, while the radial component of the target velocity v_ρ primarily induces an uncompensated linear trend on the phase history. This linear phase term causes the Doppler spectrum of the target to be shifted with respect to that of the stationary background, so some or all of the target Doppler bandwidth may go unprocessed. These effects cause the target phase history to differ from the reference used for azimuth compression, giving rise to azimuth defocus. The target will still be well focused in the range direction as long as the target Doppler does not wrap modulo the pulse repetition frequency (PRF), however. That is, despite possible target motion over several range bins during the coherent integration time, the range migration of a moving target on the correct Doppler ambiguity will be compensated during normal SAR processing.

The linear phase induced by the target radial velocity is the source of the well-known along-track shift x_{offset} of the apparent target position in the SAR imagery, which is approximated by

$$x_{\text{offset}} = -\rho_0 \frac{v_\rho}{v_{\text{plat}}} \tag{1}$$

for slow targets viewed at broadside. As a result of this shift, the interferogram pixel containing the target also contains clutter from the stationary background. The complex correlation coefficient for such a pixel is given by [4]

$$\gamma_{\text{tgt}} = \frac{S \exp(j\phi_v) + C}{S + C + N} \tag{2}$$

where S denotes the expected signal power from the moving target, C denotes the expected clutter power from the background, N denotes the expected noise power, and ϕ_v is the ATI phase expected for the target in the absence of clutter:

$$\phi_v = \frac{p2\pi}{\lambda}\frac{B_x}{v_{\mathrm{plat}}}v_\rho. \tag{3}$$

Here, v_{plat} is the platform velocity and the factor p is either 1 or 2, depending on whether or not the two SAR channels use a common phase center on transmit (or receive). From Eq. (2), it is clear that the presence of clutter causes both additional decorrelation and a phase bias, especially when the signal-to-clutter ratio (SCR) is low.

III. Experimental Results

The radar data discussed in this paper were acquired opportunistically during four calibration flights of the NASA/JPL AIRSAR system in February, April, September, and December 2004. A total of thirteen passes of data were acquired. During each pass, simultaneous C-band and L-band SAR data were collected from multiple phase centers separated along the fuselage of the DC-8 platform. The physical along-track baselines for the C-band and L-band data were 1.8 m and 19.6 m, respectively. The single-look SAR images have slant-range and azimuth resolutions of approximately 3.75 m and 0.85 m. The platform velocity and altitude above the ground surface were approximately 200 m/s and 8000 m, and the nominal single-channel PRF was about 500 Hz. During most of the passes, the radar operated in an alternating-transmit, dual-receive ('ping-pong') mode which allows for the synthesis of full, half, and zero baseline interferograms for each frequency band.

The experiment was performed in the Mojave Desert south of Rosamond Dry Lake. Several slow control targets were deployed in the imaged area: a Chevrolet S-10 Blazer; a Ford Focus wagon; a Ford F-150 pickup truck; a Subaru Legacy wagon; a bicycle towing a trailer; and a pedestrian pushing a cart. Only a subset of these targets was deployed for each flight. Each control target was instrumented with a kinematic global positioning system (GPS) unit that recorded the instantaneous target position to a post-processed accuracy of 1–3 cm at a 1–2 Hz sampling rate. No deliberate attempt was made to enhance the reflectivity of the control targets, although the GPS equipment may have affected the target cross sections. The targets moved on paved roads at horizontal speeds of 1–4 m/s.

Because a detailed examination of all targets for all passes is not feasible here, we will examine only two target acquisitions below. The F-150 target imaged on pass 170-3 of the Apr. 2004 flight serves as an example of a bright target, and the pedestrian target imaged on pass 170-2 of the Sep. 2004 flight serves as an example of a relatively dim target. Photographs of the two targets are shown in Fig. 1 (note that these photographs were not taken at the same times as the SAR overflights).

Fig. 2 depicts the single-look, half-baseline ATI signatures of the F-150 example at both C and L bands. When the SAR data were acquired, the target had along-track and across-track velocities of 0.4 m/s and 2.6 m/s, giving a radial (line-of-sight) velocity of 1.5 m/s. This target appears very bright in the SAR images at both wavelengths, perhaps because the open bed of the pickup truck (with the rear gate closed) behaves as a set of four trihedral corner reflectors. The GPS choke ring antenna was mounted on a metal tripod in the truck bed.

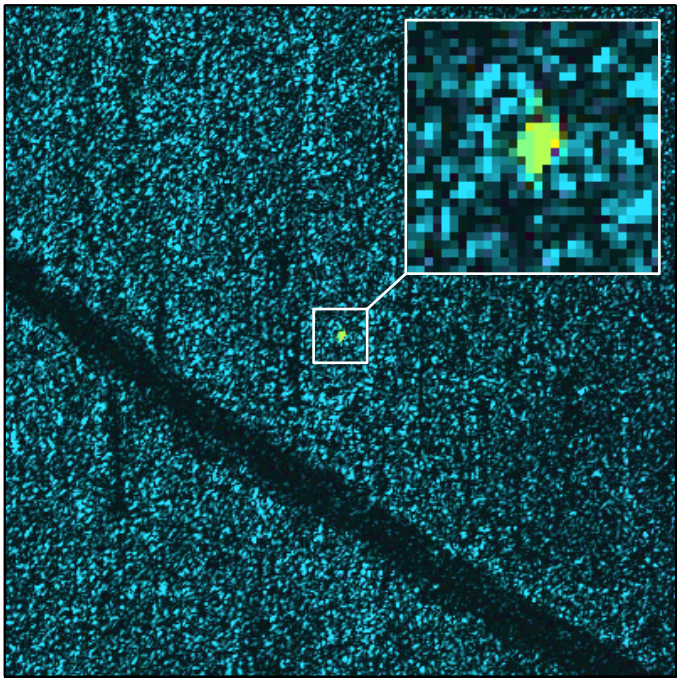
(a)

(b)

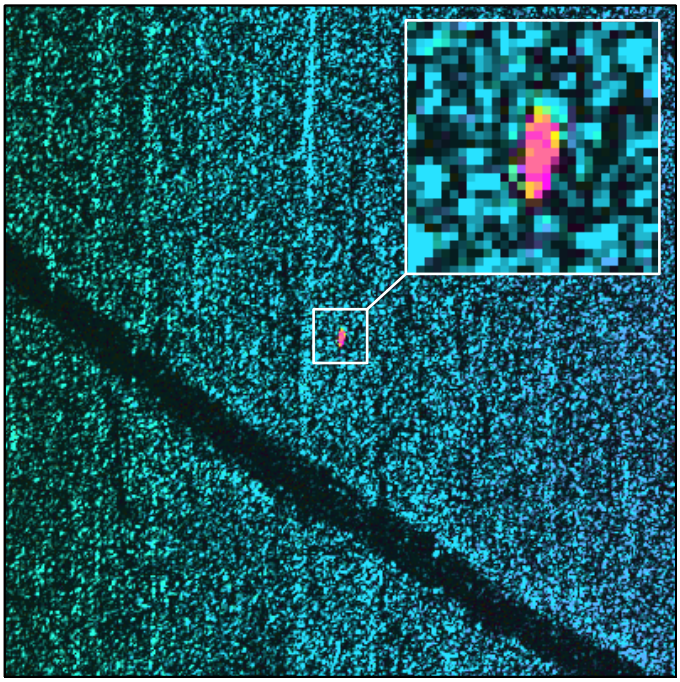
Fig. 1. Photographs of the F-150 (a) and pedestrian (b) control targets. The GPS antennas are visible in the truck bed (a) and on the upper cart deck (b).

As expected, the target is well focused in range, despite moving through several slant-range bins during the coherent integration time (approximately 3 s for C band and 12 s for L band). The target main lobe is spread over a few samples in azimuth, consistent with a quadratic phase error due to the target along-track velocity [4]. As expected, the degree of defocus is approximately proportional to the square root of the wavelength. Additional degradation of the target impulse response is also expected because of the small deviations of the target motion from linear. The target appears at the expected location in the SAR imagery to the accuracy of the measurements, accounting for the along-track shift of the apparent position. Note that the expected target location was computed using a general vector formulation rather than the approximation of Eq. (1). As is evident from Fig. 2, the brightness of the target makes its interferometric signature very clean and easily discernible from the surrounding clutter.

Fig. 3 depicts the single-look, full-baseline ATI signatures of the pedestrian example at both C and L bands. When the SAR data were acquired, the target had along-track and across-track velocities of 0.1 m/s and 1.0 m/s, giving a radial (line-of-sight) velocity of 0.7 m/s. As seen in Fig. 1(b), the target was a person pushing a steel-framed cart with a wooden deck on which the GPS equipment was mounted. A second pedestrian (without GPS equipment) followed approximately 25 m behind the cart, and a third pedestrian with a hand-held GPS unit

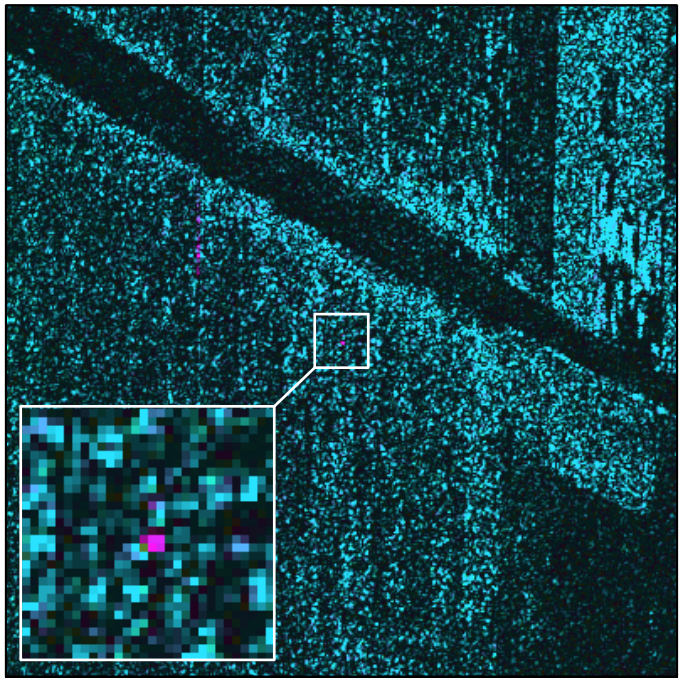


(a)

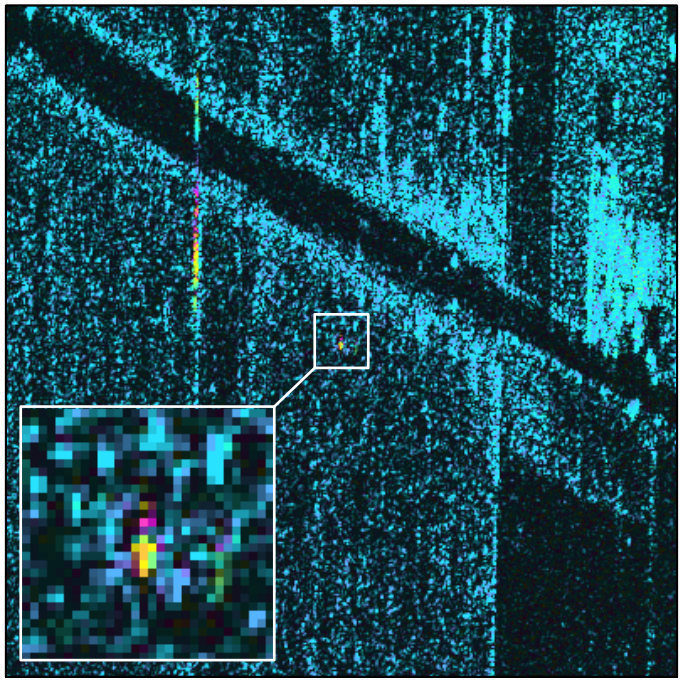


(b)

Fig. 2. Signature of the F-150 control target in the C-band (a) and L-band (b) half-baseline ATI interferograms from pass 170-3 of the Apr. 2004 flight. The full-baseline data are not shown. The interferogram phase is shown in color with a 2π rad color wrap, overlaid on a grayscale image of the interferogram magnitude. These single-look, slant-plane interferogram chips are 400×400 pixels (1330 m in slant range and 250 m in azimuth) with range increasing to the right. The enlargements are 30×30 pixels (100 m in slant range and 19 m in azimuth). The target radial velocity was 1.5 m/s. The target is reasonably well focused, although it may appear spread because of display saturation. The target along-track displacement from the road corresponds to the value predicted.



(a)



(b)

Fig. 3. Signature of the pedestrian control target in the C-band (a) and L-band (b) full-baseline ATI interferograms from pass 170-2 of the Sep. 2004 flight. The half-baseline data are not shown. The interferogram phase is shown in color with a 2π rad color wrap, overlaid on a grayscale image of the interferogram magnitude. These single-look, slant-plane interferogram chips are 400×400 pixels (1330 m in slant range and 250 m in azimuth) with range increasing to the right. The enlargements are 30×30 pixels (100 m in slant range and 19 m in azimuth). The target radial velocity was 0.7 m/s. The signature of the F-150 control target is visible towards the upper left (note that this is a different flight pass than shown in Fig. 2); this signature is severely defocused in azimuth because the F-150 was executing a turn when the data were acquired.

followed approximately 50 m behind the cart. The cart trailed a length of nylon line in an attempt to allow the three pedestrians to maintain a constant spacing. The three 60–70 kg pedestrians are each 1.7–1.8 m tall. The reflectivity of the lead pedestrian is almost certainly dominated by the cart. The two trailing pedestrians are both very dim.

While the lead pedestrian and cart appear at the expected (shifted) location in the ATI data, the degree to which the pedestrians are focused is difficult to quantify because of the surrounding clutter. Moreover, only the parts of the pedestrians that are moving at a relatively constant velocity should be well focused; the arms and legs of a person walking normally would exhibit highly nonlinear motion over the coherent integration times for both wavelengths of the SAR system.

Although the lead pedestrian and cart are too dim to be identifiable in the SAR amplitude imagery, they do appear in the ATI phase for both wavelengths. This control target is naturally more difficult to distinguish from the clutter than the F-150 upon visual inspection, however. The trailing pedestrians are not visible in the C-band data shown, but they exhibit very faint phase signatures to the right of (behind) the lead pedestrian in the L-band data shown. While it is doubtful that an automated algorithm could reliably detect the trailing pedestrians in this case, an instrument with a wider bandwidth and more power would offer higher SCR and SNR values for such targets. In data from other passes, the trailing pedestrians are sometimes more easily seen and sometimes not seen at all. They are usually more apparent in the L-band data than the C-band data.

Of all the ATI data processed during the initial round of data processing, there were 110 valid control target acquisitions between the different flight passes, targets, wavelengths, and baseline combinations. The trailing pedestrians are treated as secondary targets and are not included in this total. In 84 of these 110 opportunities (76%), the ATI signature of the control target was identifiable by a human observer with knowledge of where to look (the experiment is not 'blind'). In most of the remaining 26 cases, the predicted target phase value is near zero because of a low or wrapped radial velocity (see Fig. 4).

In cases where the control target was identifiable, the observed phase of the control target agrees with the value predicted by Eq. (3) very well, as shown in Fig. 5; the phase bias of Eq. (2) is likely very small for targets bright enough to be identified.

IV. Conclusions

We have presented results from an airborne ATI GMTI experiment which demonstrate the feasibility of the technique for detecting slow, dim ground targets. The practical utility of the technique depends on the specifics of the application, however. Brighter or faster targets may lend themselves to detection by other means. Moreover, the data described here were acquired in a relatively benign environment (flat terrain with little vegetation, steady target motion, etc.). Further, more realistic experiments will be required before the technique is mature enough for operational use.

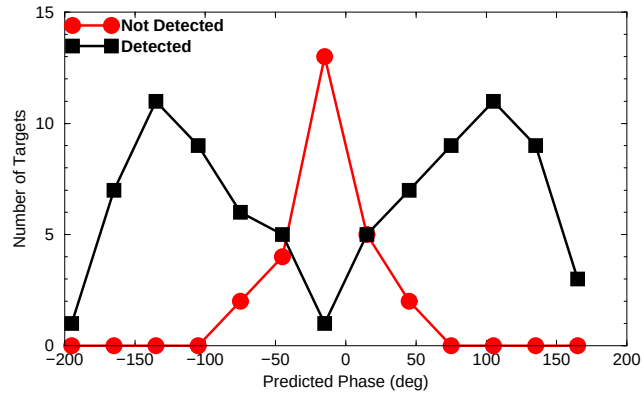


Fig. 4. Histograms for the numbers of targets detected and not detected by visual inspection as functions of the predicted target ATI phase.

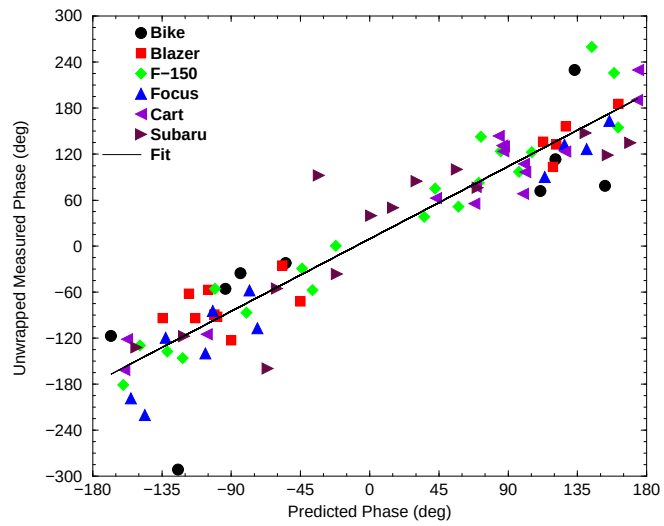


Fig. 5. Measured vs. predicted unwrapped ATI phase for identifiable control targets. The correlation coefficient is 0.94; the linear fit has a slope of 1.05.

Acknowledgments

This work was performed at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA. The authors wish to thank Anhua Chu, Michael Fitzsimmons, Michael Jourdan, Charles Le, Thierry Michel, Charles Morris, Bob Roehm, Paul Rosen, Scott Shaffer, and the JPL AIRSAR group for their help with the experiment.

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